



Feasibility of using a Stirling engine-based micro-CHP to provide heat and electricity to a recreational sailing boat in different European ports



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HIGHLIGHTS

- Feasibility study of the integration of a combined heating and power plant in a sailing boat.
- A Stirling engine cogeneration device was tested in a bench at different working points.
- Weather conditions modelled with TMY files and sea surface temperature maps.
- The simulations of the model were conducted in the Trnsys simulation environment.
- The study was performed in different European cities and results were discussed.

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ABSTRACT

This study analyses the behaviour of a Stirling engine micro-cogeneration system that supplies a sailing boat and the corresponding weather conditions and sea surface temperatures (SST) along fifteen European ports. The micro combined heating and power (micro-CHP) system was bench tested to provide information for tuning the model. The simulations of the engine and of the whole system were conducted in the Trnsys simulation environment. It was found that the Stirling-based cogeneration system is a unique source of heat for the yacht, while the produced electricity is stored in batteries and used whenever it is needed. The engine was fully integrated within the HVAC system of the boat such that the domestic hot water (DHW) tank, the heating installation and the bank of batteries can obtain energy from the cogeneration system. The conclusions of this work are based on the annual system performance.

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1. Introduction

When a cogeneration system produces a quantity of electricity less than 5 kW, the system is classified as micro-cogeneration [1]. The most commonly used micro-cogeneration technologies are fuel cells (FC), Stirling engines (SE) and internal combustion engines (ICE). The SE possesses the following additional favourable characteristics: the external combustion allows fuel flexibility [2] and the rotation elements produce less noise than an ICE device [3].

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Although the ICE is the most advanced technology and presents the possibility of trigeneration applications, such as in Míguez et al. [4,5], SE cogeneration devices are an interesting option when heat and power are simultaneously needed. Furthermore, due to the fuel flexibility advantage, the cogeneration system can be adapted to work with diesel or some other types of fuels [1,6], such as wood, pellets or natural gas. Contrary to the ICE cogeneration systems, the working periods in SE devices are considerably longer [7] because the Stirling technology uses less moving parts. Therefore, due to these and other characteristics, a SE is classified as a reciprocating external combustion engine [8] with good efficiency at partial loads [9]. Moreover, SE cogeneration devices present high thermal efficiencies and produce usable electricity; thus, it is an interesting device for isolated applications. Additionally, the reduced noise

Table 1
Locations considered in this research.

Zone	City	Country	Marina	Lat (°N)	Long (°W)
Northern European Atlantic	Helsinki	Finland	H. Segelsallskap	60.16	24.91
	Oslo	Norway	Gressholmen	59.88	10.73
	Klaipeda	Lithuania	Klaipeda	55.70	21.12
	Copenhagen	Denmark	Copenhagen	55.68	12.60
Southern European Atlantic	Warnemunde	Germany	Warnemunde	54.16	12.08
	Canvey Island	Great Britain	Halcon Marine	51.53	0.62
	Breskens	Belgium	Breskens	51.39	3.57
	La Baule	France	La Baule	47.26	−2.41
Mediterranean	La Rochelle	France	La Rochelle	46.13	−1.15
	Vigo	Spain	Marina Dávila Sport	42.23	−8.74
	Marseille	France	Marseille Vieux Port	43.29	5.36
	Dubrovnik	Croatia	Gruz - Luka	42.65	18.08
	Cagliari	Italy	Marina del Sole	39.20	9.12
	Athens	Greece	Piraeus Attica	37.93	23.65
	Malaga	Spain	R.C. Mediterraneo	36.71	−4.41

levels and vibrations of the SE are very important in recreational environments where comfort is an important consideration, such as caravans, recreational boats, etc.

The use of micro-combined cooling, heating and power (micro-CCHP) for domestic applications has also been gathering more interest in recent years [10]. One of the most commonly used technologies is a conventional vapour compression chiller because systems driven by thermal energy are still under development [10].

Because conventional refrigeration requires mechanical or electrical energy to drive the compressor [11], this cooling technology fits perfectly with SE during the summer period. Although these CCHP systems (also called trigeneration) could be an interesting option for our installation, the increase in size and price would reduce the opportunities for its application.

Some authors maintain that non-fossil fuels, in combination with cogeneration or trigeneration technologies, are the best solution for mitigating CO₂ emissions [12]. The system presented in Ref. [12] uses a heat engine (gas turbine, ICE or SE) that drives an electric generator and produces cooling power using a vapour compression chiller.

CCHP has become an interesting option for decentralised energy resources (DER) because it reduces emissions and requires less primary energy than conventional energy systems [13]. The

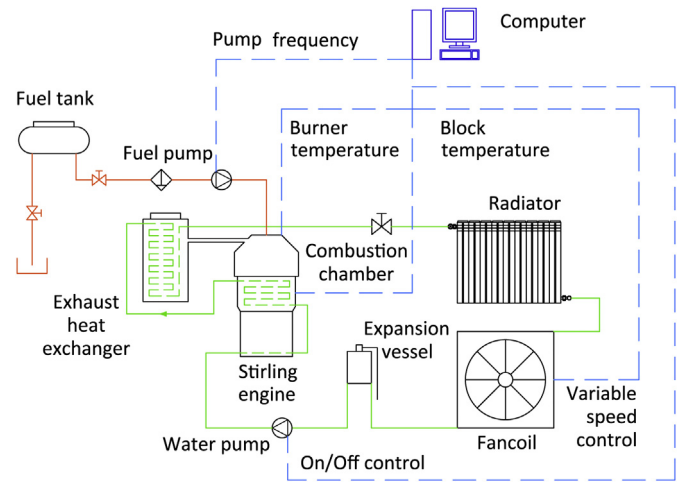


Fig. 2. Schematic of the SE experimental setup.

refrigeration and heating power is normally generated by an adsorption chiller using the heat rejected by the exhaust gases and the engine's cooling system.

Furthermore, the CHP system presented in Ref. [14] supplies different household demands using electric energy storage (EES) to cover peak demands, which improves efficiency and matches the produced energy with the demanded energy.

In Refs. [15], an ejector is used in the proposed trigeneration system to provide cooling capacity without increasing the CO₂ emissions. Ejector cycles are less expensive and mechanically simpler than absorption and adsorption cycles.

The micro-CCHP system proposed in Ref. [16] uses a small IC gas engine and an adsorption chiller.

In Refs. [17], the importance of flexibility is highlighted. In this case, a trigeneration cycle is used that incorporates a gas turbine, a steam turbine and an absorption chiller. The article maintains that the plant efficiency could be optimised by oversizing the plant, handling the different components and adapting the heating and cooling generation.

The TCS (task configuration system) used in Ref. [18] demonstrates how to optimise the design and operation of cogeneration plants.

In the thermodynamic analysis used in Refs. [19], three different ratios were analysed, including the energy conversion ratio, heating-to-cooling ratio and the electric-to-cooling ratio. Using the



Fig. 1. SE internal components and control system basics.

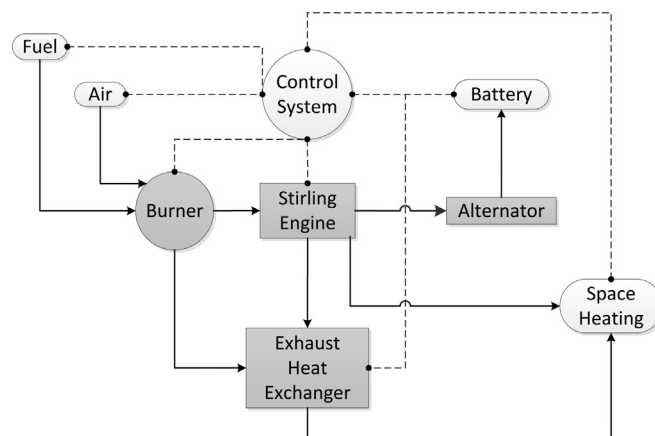


Table 2
Composition and thermal properties of the walls.

	Wetwall	Drywall		
	Fibreglass	Outer fibreglass	PVC	Inner fibreglass
Thickness [mm]	13	10	20	10
Thermal conductivity [W/m K]	0.04	0.04	0.23	0.04
Capacity [kJ/kg K]	0.84	0.84	1	0.84
Density [kg/m ³]	12	12	1500	12

last two ratios, the efficiencies of the different working points were studied.

Article [20] also studied the plant operation using a multi-objective analysis for poly-generation applications. In Refs. [21], the authors proposed an energetic, economic, and environmental analysis for trigeneration plants.

In recent years, the prevalence of recreational boats has been progressively increasing in developed countries. This type of pleasure activity presents no possibility of connecting to the conventional power grid unless the boats are moored and connected to the coastal power supply. Therefore, the type of cogeneration system studied in this work is especially interesting for use during cruising and offshore operations. For recreational sailing boats, the proposed system becomes even more interesting due to the absence of noise and vibrations and, particularly, because the propulsion system of the boat is turned off for the majority of the sailing and anchoring time.

The TRnsient System Simulation (Trnsys) programme [22] was developed to solve complex energy system problems. The modular structure of the programme facilitates the definition of new components. Trnsys has been successfully used in numerous works. Campos-Celador et al. used the Trnsys software to apply a thermoeconomic analysis to a micro-cogeneration installation in a tertiary sector building [23], Pagliarini et al. [24] used Trnsys to optimise CHP systems in a hospital, Magri et al. [25] used Trnsys to analyse the electric and thermal seasonal performance of a Stirling micro-CHP unit in a residential building, and Dorer et al. [26] used it to conduct a performance assessment study for micro-cogeneration systems and residential buildings.

To simulate the yacht under average ambient conditions, the Meteornorm database was used [27], which is software that generates a text file with the data of a typical meteorological year (TMY) for practically any location in the world. This database has also been employed to obtain the sea surface temperature (SST) as a boundary condition for modelling the heat transmission through the hull of the yacht in contact with the seawater.

The geographic focus of this study is Europe. The European coast is divided into the three following areas depending on the climatic distribution: Northern European Atlantic, Southern European

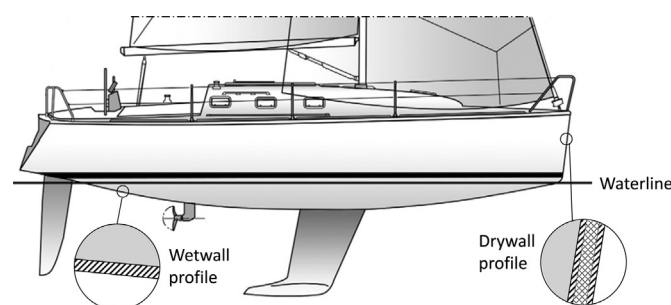


Fig. 3. Wetwall and drywall profiles.

Table 3
Electrical equipment rated consumption and daily utilization.

	Electrical consumption (W)	Utilization (h/day)
Engine compartment fan	72	1.00
Indoor lights (LED)	85	4.00
Outdoor lights	15	2.00
Autopilot	792	1.80
Fresh water pump	62	1.00
Fridge	29	6.00
Electric toilet	120	0.60
VHF and GPS stations	103	6.00
Tv 20" + DVD	120	2.00

Atlantic, and Mediterranean. Five port cities were selected in each of these areas. Table 1 shows the areas with the selected cities and marinas as well as their latitudes and longitudes.

2. Experimental analysis

The Stirling engine and the sailing boat used in this study are presented.

2.1. The Stirling engine

The selected SE is the smallest commercially available on the market. This engine has a block with four cylinders that are filled with nitrogen at a maximum pressure of 28 bar at 70 °C. The nitrogen is heated and works in a closed thermodynamic cycle [7] that provokes the alternating displacement of the four pistons [2]. This movement is converted via a wobbling system in the rotational movement of an alternator. The produced electricity can be directly consumed or accumulated in a battery bank. The built-in control system of the SE modulates the electrical energy produced to manage the state of charge (SOC) of the battery bank.

The reduced dimensions (450 × 500 × 650 mm³) and reasonably light weight (90 kg) of this cogeneration system make it an interesting choice of equipment for its implementation in mobile applications or small isolated houses. Fig. 1 illustrates the main components of the SE. The SE cogeneration system produces heat for space heating and produces electricity with an estimated overall ratio of 6:1 (heat to electricity ratio).

2.1.1. Working details

The SE control system will operate with different control strategies depending on the parameters measured by its sensors. An external diesel burner produces the required heat for the entire

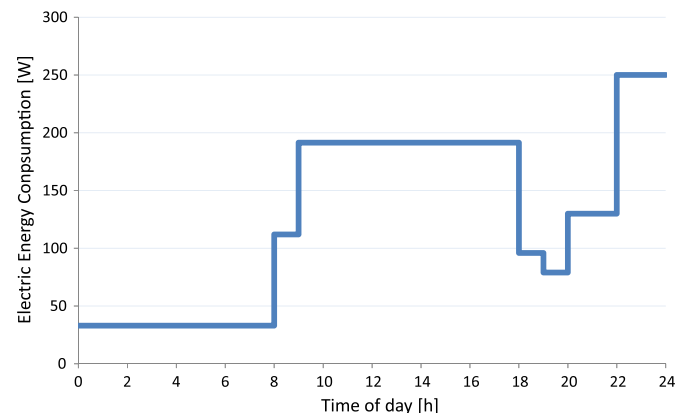


Fig. 4. Electricity consumption during a typical day.

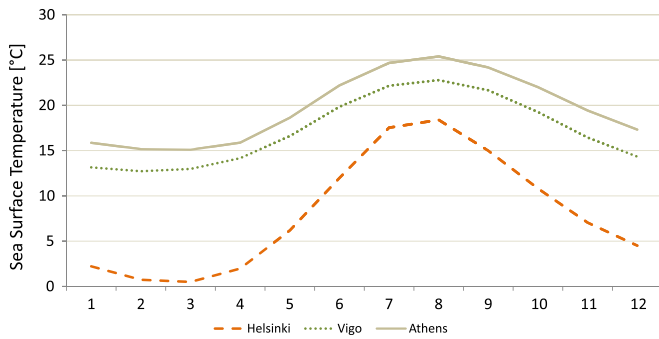


Fig. 5. Monthly SST in Helsinki, Vigo and Athens.

system. A variable speed blower introduces the air, while a frequency-controlled fuel pump controls the air-to-fuel ratio in a closed loop via an oxygen sensor immersed in the exhaust gases leaving the system.

The SE management system can give priority to the heating load or to the SOC of the battery bank. If the heat management system is turned ON, priority is set to the production of heat; therefore, once the SOC is 100%, the extra electricity produced by the alternator is converted into heat in a resistance system called a *clamp* and is then used to increase the amount of heat produced by the system. In this mode, the SE produces its maximum heating output of approximately 7 kW.

Alternatively, the SE can operate in auto-charge mode (heat management OFF) in which the SE is devoted to maintaining the SOC of the batteries. When the SOC drops below the minimum set-point, the SE cogeneration system will automatically turn on and operate at its maximum electrical output until the SOC reaches 100% or until the optional maximum operational time is reached, after which the SE automatically turns off. The heat produced during this operation is sent to the consumers or dissipated in a secondary loop.

2.1.2. Test bench

The SE cogeneration system has been extensively tested in the laboratory to obtain the working parameters and understand its running modes. Because the SE control system allows the set-point temperature of the block to be adjusted between 45 and 70 °C, modification of the operating temperature of the cooling system is

enabled. During the SE experiments, the set-point temperature was set at 60 °C because it is the standard value for the radiators and fan coils employed in heating systems.

The SE was tested on a laboratory bench with four controlled circuits (fuel, air-gas, water and control). The electrical and hydraulic circuits transported the power and heat produced by the SE to the consumer. Fig. 2 shows the main parts of the experimental plant that was constructed for testing and characterising the system.

Two batteries connected in series constituted the battery bank with a total capacity of 100 Ah and a nominal voltage of 24 V. As shown in Fig. 2 the coolant circulates through the engine block and through a gas-to-water heat exchanger, which recovers part of the energy that is not converted into electricity by the engine. Therefore, the circulating water recovers heat from the block and from the exhaust gases, which maintains the exhaust temperature at the exit of the system at approximately 90 °C. This flow of hot water is then sent for consumption (radiators and domestic hot water system), while a fan coil ejects excess thermal energy before the cooling water is sent back to the engine. Flow is measured using a volumetric flowmeter, and two temperature sensors are used to measure the difference in temperature. The current going into or out of the batteries is measured using a Hall Effect ammeter. During the tests, many other parameters were also measured, including the gravimetric fuel consumption, exhaust gas composition, exhaust gas temperature, battery voltage, temperature and estimated SOC, burner and block temperature, and many other parameters related with systems control and management.

Data from the different sensors is registered every second. This frequency allows the accurate measurement of the electric energy produced, heat recovered and thermal and electric efficiencies and their variation with time.

The software Micromon V1.0 was used to collect the data produced by the SE and an interface programmed in LabVIEW recorded the information from the sensors distributed throughout the installation.

The system was tested at different working points. Several electrical loads between 350 W and 900 W were generated using 24 V halogen lamps. This power load simulates the possible electrical consumption while the radiator and the fan coil of the test bench replace the heating and the ACS demand of a conventional sailing boat. Tests were performed until steady state was reached. The results will be presented in the next section. The results will be presented in the next section.

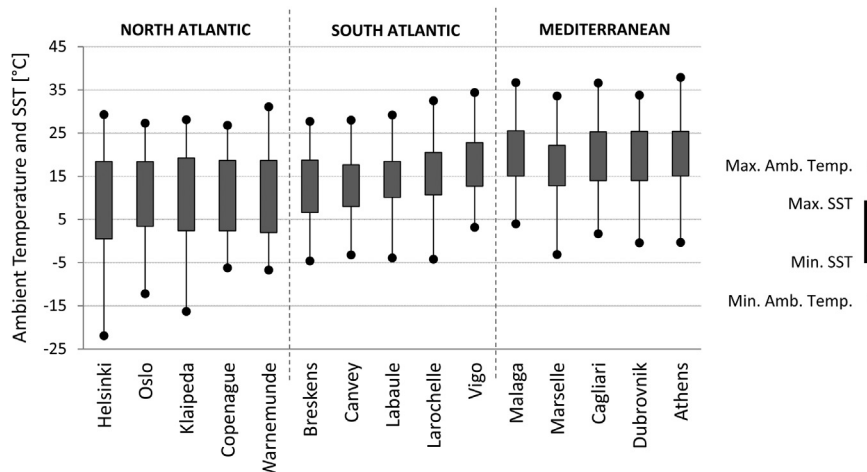


Fig. 6. Maximum and minimum values for ambient temperatures and SST in all locations.

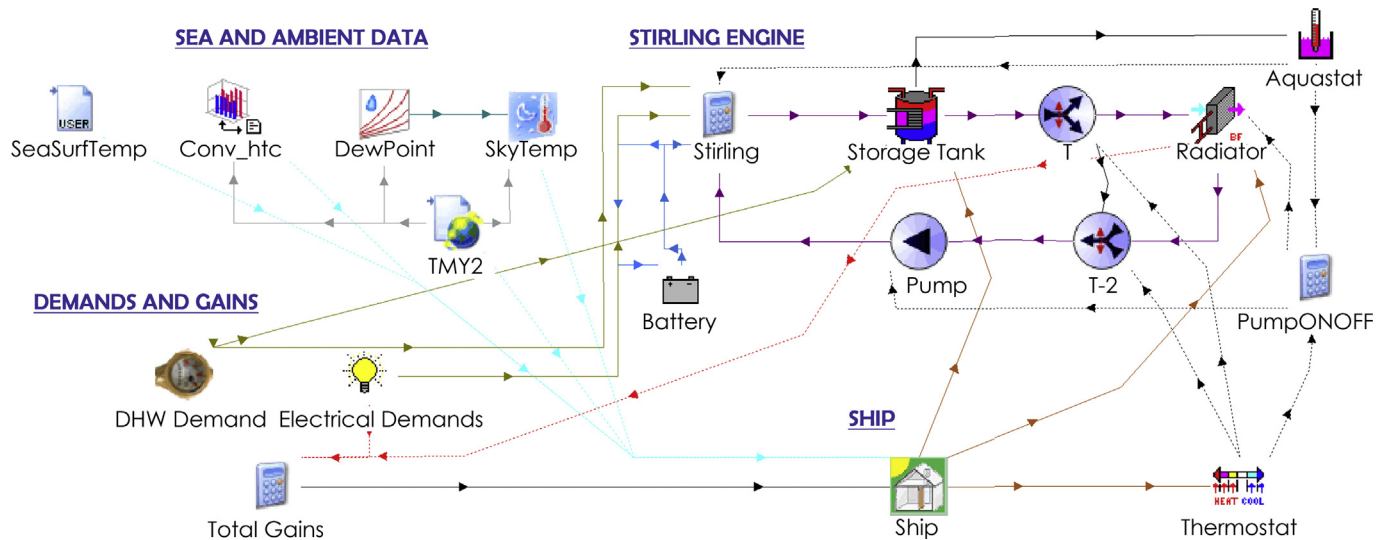


Fig. 7. Trnsys simulation of the SE cogeneration system on board.

2.2. Sailing boat

For this study, a pleasure sailing boat that requires heating and electricity was considered. Because powerboats have a large main engine, they can easily generate electricity and heat. Sailing boats operate most of the time with the engine off, making it more difficult to charge the batteries. In addition, the engine power is normally very low because these boats usually carry a small motor that is only used for low speed coastal movements. Furthermore, recreational motorboats usually incorporate a heat pump that provides hot air in the winter and air conditioning in the summer, whereas sailing boats often carry no heating systems because they consume very high amounts of electricity and could only be used when “plugged in” to the port. For this reason, recreational sailing boats are considered to be best suited for the present study. The selected vessel is 10.36 m long.

The vessel is modelled using the Trnsys program TRNBuild. For this purpose, the boat enclosures are classified as wetwall or drywall, and each enclosure type has a different composition. The compositions and thicknesses of the walls, ceilings, and floors of the boat are presented in Table 2.

The drywall surface area, including the deck, is 70.63 m²; the wetwall surface area, which is in contact with the water, is

23.89 m²; and the total volume of the vessel is 47.78 m³. The interior capacitance of the boat is calculated by multiplying the total volume of the vessel by ten to consider the thermal inertia of the furniture. Air renewal is considered to be 0.6 renovations per hour with a fixed comfort temperature of 20 °C.

Fig. 3 shows the compositions of the drywall and wetwall of the sailing boat.

To perform the simulation, the power consumed by the vessel must be known. The following electric consumers have been identified and their use over a regular day estimated. Table 3 shows the power demands and times of each of the electric consumers considered in the boat.

Table 3 shows a summary of the equipment incorporated into the boat along with the consumption of each system.

Based on the available information, a daily consumption profile is constructed. The resulting distribution profile is shown in Fig. 4.

3. Methodology

Weather conditions and sea temperatures will be established for all the locations identified in the first section of this chapter. The dynamic models used in the Trnsys simulations will be detailed in the second part.

Table 4

Maximum heat demand for all locations in kW. Month, day and time of the maximum heat demand. Ambient and sea surface temperatures in °C.

City	Maximum heat demand (kW)	Month of maximum heat demand	Day of maximum heat demand	Time of maximum heat demand	Air temperature (°C)	SST (°C)
Helsinki	4.35	2	15	8:06	−21.9	0.7
Oslo	3.43	2	15	0:36	−11.4	3.5
Klaipeda	3.68	1	12	19:30	−15.8	4.1
Copenhagen	2.97	2	15	2:48	−5.9	2.4
Warnemunde	3.04	1	12	9:00	−6.7	2.8
Breskens	2.61	1	12	21:06	−4.5	7.4
Canvey	2.50	1	13	1:30	−2.9	8.8
LA Baule	2.43	1	13	7:36	−3.1	11.0
Larochelle	2.44	1	13	1:06	−3.8	11.6
Vigo	1.74	1	15	9:12	4.6	13.1
Malaga	1.72	1	12	9:00	4.0	15.5
Marseille	2.22	12	25	8:12	−1.0	14.4
Cagliari	1.82	1	13	8:00	1.7	14.7
Dubrovnik	1.96	1	13	1:06	1.4	14.3
Athens	1.88	2	15	4:36	0.3	15.2

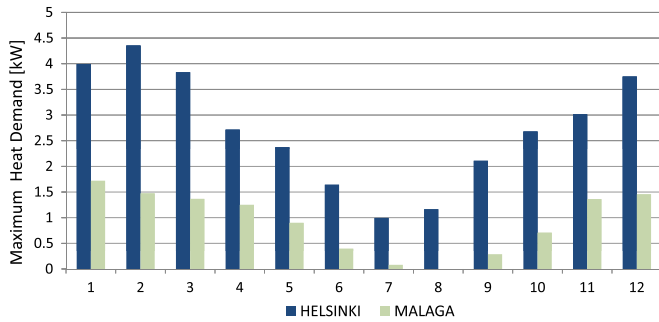


Fig. 8. Monthly maximum heat demand for Helsinki and Málaga.

3.1. Weather conditions

The average seawater temperatures are provided by the National Center for Atmospheric Research (NCAR). The dataset is freely available in the network common data format (netCDF) through the Community Data Portal [28]. The average data from the last ten years were extracted for all the selected locations, and the total average temperature was calculated. The hourly data were interpolated from these values.

Fig. 5 shows the SST for Helsinki, Vigo and Athens.

The ambient temperatures were provided by the Meteornorm software for all the investigated cities. Fig. 6 shows the maximum and minimum values of the ambient temperatures and SST in all the cities under study.

3.2. Trnsys simulation

A dynamic model of the yacht and the HVAC installations was created in Trnsys based on the available components. The yacht was modelled as a Type 56 with a single thermal zone with the external walls in contact with the ambient air or seawater. In the simulation, two batteries with 24 V and 100 Ah capacities were introduced to restrict the maximum capacity of electric generation. This bank of batteries also facilitates the supply of electrical energy when the SE is turned off. A small inertia tank of 60 L prevents continued starts and stops and also simulates the thermal inertia of the system itself.

The SE is simulated in a quasi-steady state and modelled using an equation that controls the state of charge of the batteries. If the bank of batteries is full, the electrical power is added to the thermal energy using the clamp as previously mentioned. When the indoor temperature drops below 21 °C, the fan coils from the HVAC system introduce heat into the yacht. The consumption of DHW is simulated on a schedule with a constant daily value of 144 L (assuming an average of 3 passengers). Electrical demand is also simulated using schedules and reaches an instantaneous maximum consumption of 250 W when several loads coincide in time.

Separate hourly simulations are performed for all locations to obtain the annual maximum thermal load at each of the localities to

Table 5
Steady state electric and heating power for the different electric loads.

Test number	Electric load (kW)	Electric power generated (kW)	Heating power (kW)	Fuel consumption (kg/h)
1	0.350	0.918	5.851	0.647
2	0.400	0.919	5.954	0.633
3	0.450	0.932	6.095	0.637
4	0.500	0.933	6.057	0.645
5	0.550	0.931	6.016	0.643
6	0.650	0.929	5.980	0.641
7	0.750	0.932	5.978	0.642
8	0.950	0.904	5.770	0.641

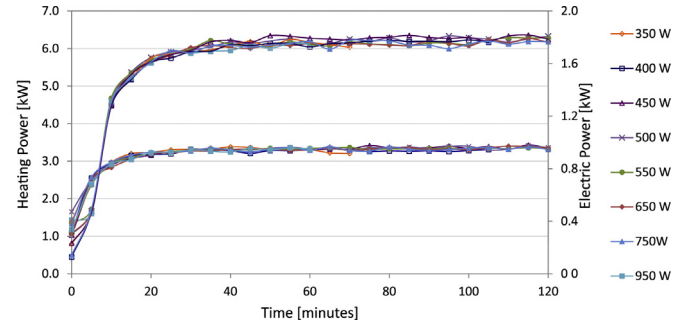


Fig. 9. Electric power (higher) and heating power (lower) produced during the different tests.

determine whether the proposed system produces sufficient power to meet the demands of the yacht. For this purpose, an ideal heating system was configured to maintain the temperature inside the vessel at a minimum value of 20 °C. Through this simulation, TrnBuild can determine the necessary thermal peak power.

Additionally, a simulation was conducted in each city to obtain the thermal and electrical outputs from the SE. The yacht is linked to components that simulate the weather, the gains and internal consumption, and the heating system and the components. Fig. 7 shows the layout of the graphical environment of this simulation.

4. Results

Results are presented as thermal load analysis, experimental results, and simulation results.

4.1. Thermal load analysis and SE suitability

As mentioned above, a study of the maximum monthly and annual thermal loads for each chosen location was conducted. The study of these thermal loads was performed considering a comfort temperature inside the boat of 20 °C. The simulation results are summarised in Table 4 along with the maximum annual thermal loads at the different locations and the dates and times of the occurrence of these loads. The air temperatures and the SSTs are also shown.

In Table 4, the investigated cities are ranked by the maximum heating rate. The city where the heat demand is the greatest is Helsinki, with a peak thermal demand of 4.35 kW, and the lowest peak demand is in Málaga at 1.72 kW. It is also observed that Vigo has a low peak demand, despite being within the Southern Europe Atlantic group; however, Marseille has a peak demand closer to

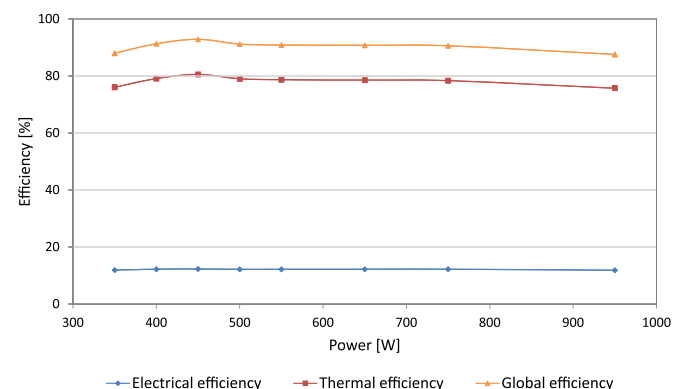


Fig. 10. Experimental efficiencies at different loads.

Table 6

Monthly heat produced for all locations, in kWh.

Month	1	2	3	4	5	6	7	8	9	10	11	12
Helsinki	2323	2121	2052	1403	931	595	458	558	910	1451	1794	2187
Oslo	2016	1803	1750	1239	869	582	477	586	838	1315	1599	1949
Klaipeda	2075	1864	1766	1199	819	559	418	466	740	1228	1564	1885
Copenhagen	1885	1696	1673	1192	809	596	469	513	764	1166	1466	1765
Warnemunde	1860	1646	1577	1120	778	572	469	497	713	1102	1426	1769
Breskens	1620	1432	1358	973	742	551	459	460	614	929	1240	1579
Canvey	1472	1330	1302	983	823	606	511	508	634	883	1177	1442
LA Baule	1380	1208	1080	830	658	483	444	458	574	806	1066	1341
LA Rochelle	1344	1150	1036	773	601	410	375	382	491	710	1029	1306
Vigo	1047	877	834	685	546	389	341	342	414	583	857	1041
Malaga	902	741	700	553	421	290	260	258	295	431	679	845
Marseille	1211	1040	909	692	497	337	293	300	421	606	907	1198
Cagliari	982	864	810	646	451	310	262	262	313	429	677	921
Dubrovnik	1098	937	862	632	393	280	255	260	332	491	768	1020
Athens	938	861	770	587	401	272	250	253	291	412	616	860

other Atlantic cities. Therefore, the peak thermal demand is strongly related to latitude, despite the positions of Vigo on an oceanic coast and Marseille on a Mediterranean coast.

Fig. 8 shows the maximum monthly loads for the extreme cities, Helsinki and Málaga.

During the summer, the city of Málaga requires practically no heating. It has to be considered that the energy requirement for DHW was not considered during this analysis. This load is taken into account afterwards, which increases the heating demand on the system. After analysing the maximum power required, the SE is considered to be a valid option for heating the selected vessel with the characteristics described above, regardless of its geographic location.

4.2. Experimental results

The electrical and thermal powers and the fuel consumptions were analysed during different tests, and the results are presented in Table 5 for different electrical loads under steady state conditions.

In Fig. 9, the electric energy power outputs from the SE bench test are presented. These results reflect that the SE almost always operates at its rated power, regardless of the electric load. Any excess electricity generated is employed to recharge the battery bank or to increase the heating power output using the clamp. This working point allows the SE to operate with a good efficiency, although it limits its modulation capacity. This operational point is calculated as an average of the different values. Therefore, the

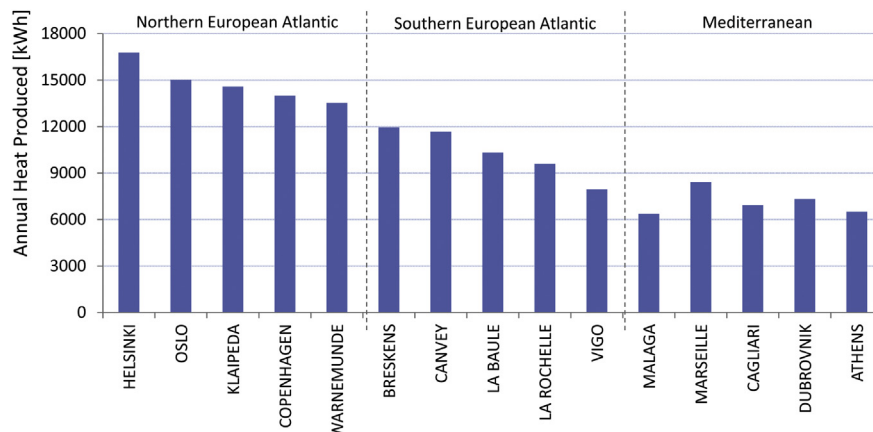
thermal power of this operational mode is 5.93 kW, and the average electrical power output is 0.92 kW. During the different tests, the fuel consumption stabilised at approximately 0.64 kg/h. These values will be used for the Trnsys simulation.

Because the operational point is almost the same, the overall efficiencies are not sensitive to the power load as the efficiencies are almost constant. The ratio between the generated heat and electricity is 6.5:1 (5.93 kWt to 0.91 kWe), and the global efficiency is approximately 91%, as illustrated in Fig. 10, whereas the electric generation efficiency is approximately 12%.

Table 7

Monthly electric energy produced for all locations, in kWh.

Month	1	2	3	4	5	6	7	8	9	10	11	12
Helsinki	94	85	94	91	85	71	65	72	86	94	91	94
Oslo	95	85	94	90	83	72	68	76	85	94	91	94
Klaipeda	94	85	94	89	81	70	62	67	81	94	91	94
Copenhagen	94	85	94	90	83	73	66	70	83	94	91	94
Warnemunde	94	85	94	88	80	70	66	68	80	92	91	94
Breskens	94	85	94	87	80	71	66	66	76	92	91	94
Canvey	94	85	94	86	83	74	69	70	77	90	91	94
LA Baule	94	85	92	84	76	64	63	63	70	88	91	94
LA Rochelle	94	84	91	80	74	59	57	59	65	82	91	94
Vigo	93	83	86	76	68	57	53	53	59	75	88	94
Malaga	91	78	77	66	60	45	40	40	46	63	79	89
Marseille	94	84	86	77	67	52	46	47	61	77	88	94
Cagliari	92	81	83	75	64	48	41	41	49	63	80	90
Dubrovnik	93	83	87	77	59	44	40	40	51	70	85	93
Athens	90	81	82	71	59	42	39	39	45	62	76	89

**Fig. 11.** Estimation of the annual heat produced in all locations.

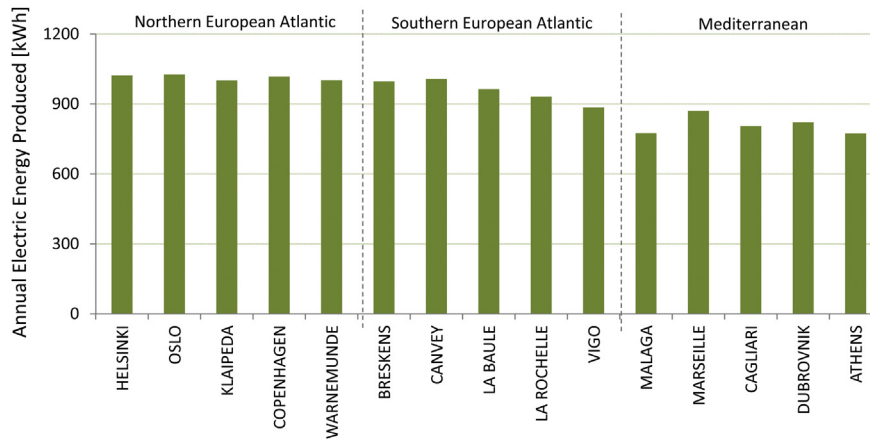


Fig. 12. Estimation of the annual electricity produced in all locations.

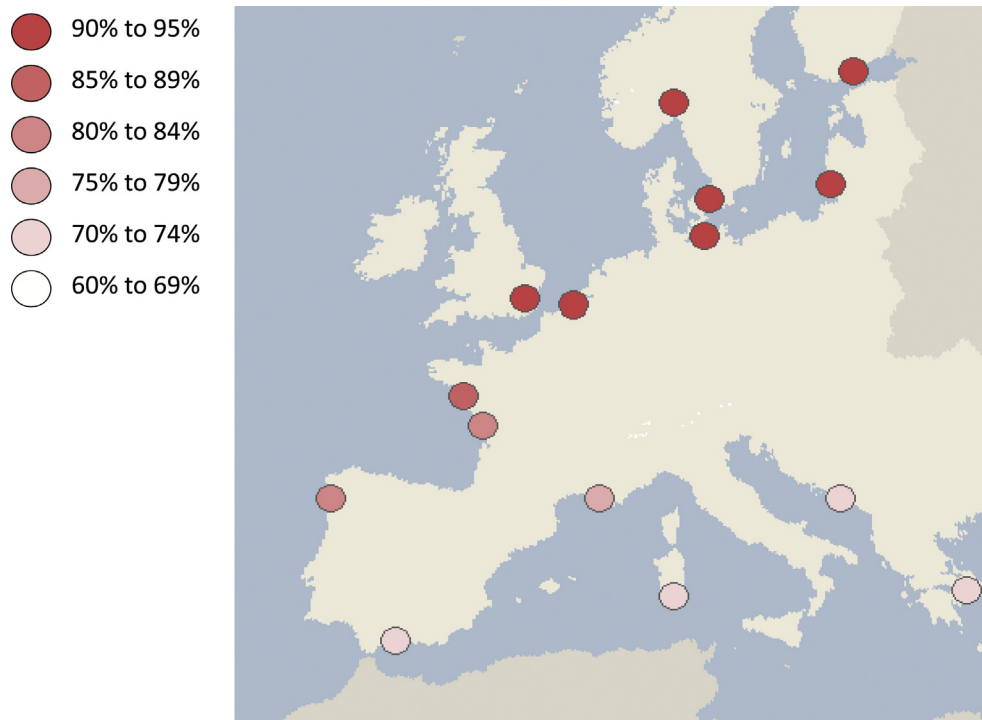


Fig. 13. Percentage of annual electric energy demand covered by the SE.

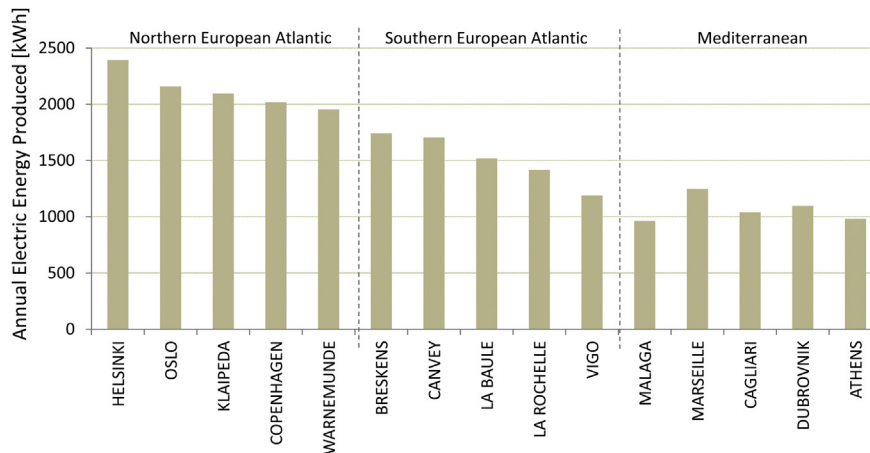


Fig. 14. Annual electric energy produced considering energy consumed in the clamp.

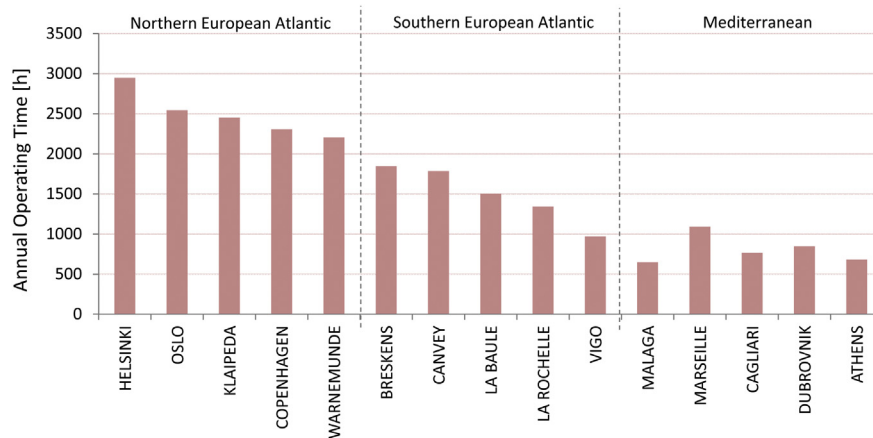


Fig. 15. Annual operating time in all locations.

4.3. Simulation results integrating the SE cogeneration system

Table 6 shows the monthly thermal output from the SE in kWh at different study sites, and Fig. 11 shows the total annual accumulated value in kWh. These values range from more than 2000 kWh in the colder months in Northern locations to 300 kWh in Mediterranean locations during the summer months (justified by the demand for DHW production). The annual thermal production values are between 2 and 2.5-times greater in northern European locations than in Mediterranean locations.

Table 7 shows the values of electricity production in kWh for every month of the year in the 15 studied localities, while Fig. 12 shows the annual values. Note that in this study, electricity is produced as a by-product of heat because the system operates with a large battery bank and because the operation of the system as electricity-only is very inefficient; therefore, the existence of an alternative power supply is assumed at the required locations. The obtained monthly values are between 95 kWh and 39 kWh. Because the average monthly consumption is 92.2 kWh, the upper value is limited around that value. During the summer months, at least 42% of the demand is met.

The fraction of electricity demanded by the yacht that can be met by the SE is approximately 70% in Mediterranean countries and is over 90% in colder countries, as shown in Fig. 13. In fact, part of the electrical energy produced is lost due to lack of capacity in the battery bank. If the energy consumed by the clamp is added to the energy produced and stored in the batteries, the total electrical energy demand could have been generated. In fact, the number of hours the clamp is used to dissipate excess electric energy that the battery bank could not contain is more than one-third of the annual hours in northern cities, such as Helsinki, Oslo and Klaipeda. In these circumstances, the SE works as a heat engine and the electricity produced by the alternator is converted into heat using the clamp. It can be inferred that the simulated electricity demand is too small for a production ratio of 6.5:1.

Fig. 14 shows the total electrical energy that could have been generated if there was sufficient storage on the yacht. These numbers were calculated by combining the energy stored in the batteries and the electric power consumed in the clamp over the course of a year. In northern countries, the system can generate between 2 and 2.5-times more energy than in southern countries.

Fig. 15 shows the total hours for which the SE is in operation. This number is between 3 and 5-times greater in colder locations, which require higher amounts of diesel consumption.

An important value is the number of hours where the batteries are depleted. In the hottest cities, for approximately 2000 h of the

8760 operational hours (23.1%), the yacht must have another type of electrical generator or the SE operates only as a generator, rejecting the excess thermal energy (conventional genset mode). The presence of solar panels or wind generators could cover the lack of power of the system, reducing the number of hours operated in the low efficiency genset mode to a minimum.

To make a monthly comparison of the results of the simulations, three representative cities were chosen according to the number of hours the SE is running (Helsinki in the north, Marseille in the Mediterranean and Breskens as an intermediate climate). Fig. 16 shows the annual hours with heating and/or DWH demands for the three cities, which indicates the operational hours. In the summer months, there is less difference between the cities because heat consumption is essentially only due to DHW demand.

Fig. 17 shows the relationship between the demanded monthly electric power and the power generated by the SE. For a boat with the described electric and DHW consumption, the SE is shown to be a valid micro-cogeneration system because it produces more than 90% of the electricity consumed by the yacht for 8 months of the year, whereas during the summer period, more than 70% of the demand is met in cities such as Helsinki. In cities like Marseille, the electrical demand is covered in excess of 90% for five months out of the year, while the values in summer months are closer to 50% and additional power must be provided by any of the previously mentioned means.

Yacht size and type are important and very relevant for the results of this study as heat and electric energy demands principally depend on these two variables. Other variables involved are: equipment, infiltrations, ventilation, etc. The results obtained could

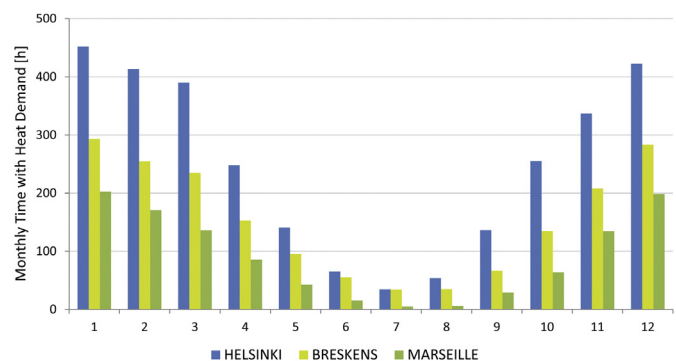


Fig. 16. Monthly time with heat demand for Helsinki, Breskens and Marseille.

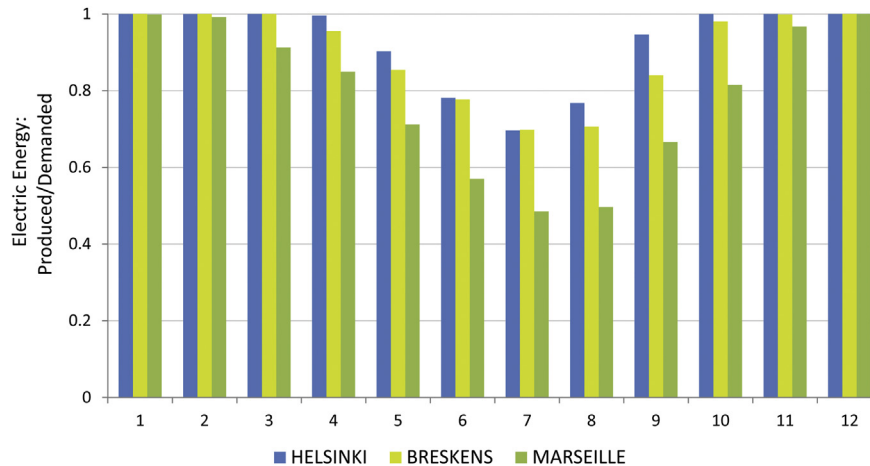


Fig. 17. Monthly ratio between produced and demanded electric energy.

be extrapolated to different situations as long as the relationships between yacht demands and capacities of the components of the micro-CHP system are similar to those employed in this study.

5. Conclusions

In this work, the feasibility of employing a micro-cogeneration Stirling-based system is studied as applied to heating and DHW generation on a yacht. An experimental analysis of a commercial SE was performed to provide values for generating a model of the SE installation with an inertia tank and electric batteries. The model was developed in the Trnsys simulation studio using the SSTs of 15 European cities, and the weather conditions were modelled using the Meteororm software, which generates TMY files for all the selected locations.

The results show that the SE is a valid system in vessels such as the one analysed. Simulations show that the maximum heating demand is approximately 2-times higher in northern Europe than in southern Europe; therefore, thermal generation has to meet this demand, indicating that power generation will also be between 2.0 and 2.5-times greater in the northern locations than in the southern locations. Hence, the electrical demands are fully met in the coldest countries, while they are satisfied only in the colder months in the south and only 50% of the electric energy demanded is met in the warmer months. Consequently, the number of operating hours of the SE in the north is between 3 and 6-times that in the Mediterranean countries.

Further studies could be focused on fixing the geographic variable while boat type or size varies. This kind of study could be useful to check the suitability of SE micro-CHP for different kind of boats at the same location.

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